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Narrowband Z-mode emissions interior to Saturn's plasma torus

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[1] During Cassini's close approach to Saturn, on 1 July 2004, a set of narrow bandwidth plasma emissions were detected by the Radio and Plasma Wave Science (RPWS) instrument in the inner magnetosphere. These discrete tones were detected between 3 and 70 kHz, with individual tone bandwidths as low as a few hundred Hertz. The tones persisted for long times (~ 1 hour) as Cassini flew in planetocentric radial distances of less than $2.5 R_s$. During this time at lower radial distances, the spacecraft passed inside the inner edge of a clear and distinct plasma torus; this torus is located between 2.2 and $\sim 10 R_s$. We describe the emissions, and demonstrate that the mode of propagation is the Z-mode. The emissions are found to originate at locations where electron plasma oscillations along the plasma torus edge are relatively intense. We describe a mechanism for f_p electrostatic-to-electromagnetic wave conversion to explain the origin of the narrowband Z-mode tones. The tones allow remote-sensing of the plasma torus and indicate that the torus is dynamic, with changes in density in the tens of percent over the course of an hour.

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1. Introduction

[2] On 1 July 2004, the Cassini spacecraft made its historic orbit-insertion into the Saturnian planetary system. The 103 minute capturing burn occurred as the spacecraft approached to within $1.4 R_s$ of the planet, where it flew from the southern dayside region, over the northern top of the rings, and into the southerly nightside. Onboard Cassini was the Radio and Plasma Wave Science (RPWS) instrument, consisting of five radio receivers, a sounder and a Langmuir probe to detect the magneto-plasma wave environment [Gurnett *et al.*, 2004]. During this closest approach period, the plasma density was monitored via naturally generated upper hybrid (UH) waves, Langmuir waves, whistler emissions and detected directly via the Langmuir Probe and Sounder. Numerous new plasma wave emissions were also detected from the inner Saturnian magnetosphere and have been recently reported by Gurnett *et al.* [2005]. In this paper we focus on one of the electromagnetic emissions: narrowband tones detected in the inner Saturnian magnetosphere, located adjacent to the wall of a plasma torus.

[3] Figure 1 shows an overview RPWS high and medium frequency receiver spectrogram of the close encounter period, when the spacecraft was within $4 R_s$ of Saturn. The primary emissions are indicated in the figure, including intense emissions from the spacecraft orbit insertion burn

(01:07–02:52 SCET) and broadband burst/dust impacts at the ring plane crossings (00:45 SCET and 04:32 SCET). Throughout the CA period, the local electron plasma frequency, f_p , revealed itself via intense emission at the UH resonance in high density regions where the plasma frequency is greater than the electron cyclotron frequency, $f_p > f_c$ (before 01:00 SCET and after 04:15 SCET) and via intense f_p emission in low density regions where $f_p < f_c$ (between 01:00–04:15 SCET). The inferred electron density $N_e (= f_p^2/81, f_p$ in units of kHz) from these wave modes has been confirmed with direct Langmuir probe observations. This electron density, adapted from Gurnett *et al.* [2005], is plotted in the top panel of Figure 1. The electron density profile reveals the presence of a substantial Saturnian plasma torus with peak densities near 150/cc at about 2.2 – $2.4 R_s$ [Gurnett *et al.*, 2005]. Inside of $\sim 2.3 R_s$, the densities drop abruptly by three orders of magnitude over a relatively short distance of $< 1 R_s$, indicating that the torus inner edge is a very steep gradient (particularly during the outbound passage, with measurements uncontaminated by noise from the spacecraft burn).

[4] Richardson and Jurac [2004] indicate that this torus is related to the sputtering of neutrals from the icy moons. Their Figure 1 shows the modeled torus extending out to beyond $12 R_s$, with electron densities exceeding 100 el/cc near $3 R_s$ and with a very steep gradient near $1.8 R_s$. The RPWS observations are consistent with the high density torus, but with the peak densities lying closer to $2.2 R_s$ making the observed gradient even steeper than that modeled.

[5] The RPWS instrument could also monitor the magnetic field via naturally generated $(n + 1/2) f_c$ harmonic emissions in regions where $f_p > f_c$ and as a weak upper hybrid emission $f_{uh} \sim f_c$ in regions where $f_c > f_p$. These

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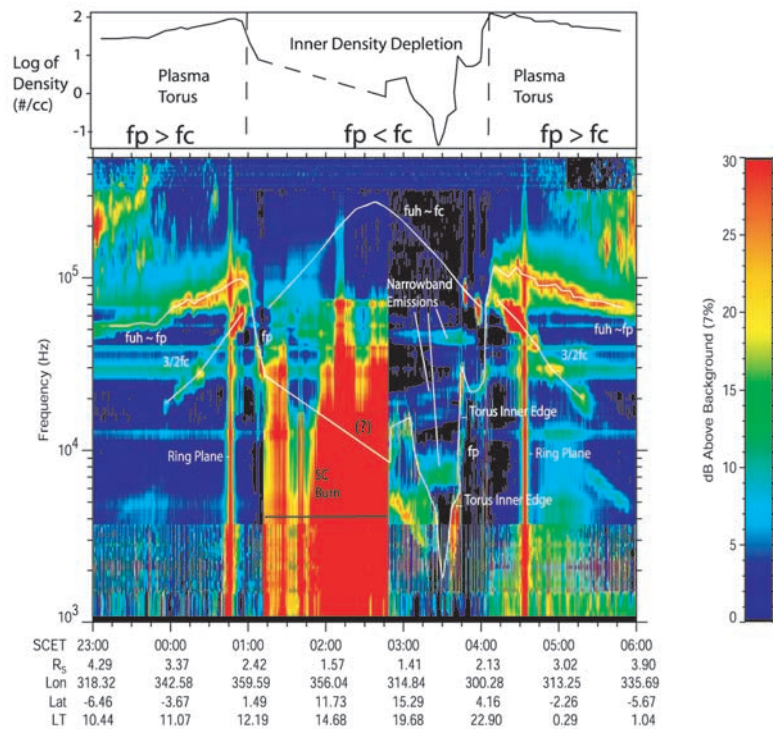


Figure 1. A Cassini RPWS spectrogram from 1 July 2004 presenting an overview of the orbit insertion/closest approach period. The spacecraft flew through a plasma torus with peak electron densities exceeding 100 el/cc near 2.2 R_s . Thereafter, the densities quickly decreased as radial distance decreased. The question mark during the burn indicates that the plasma frequency line is an interpolation during this period.

emissions are identified in Figure 1. The Saturnian magnetic field derived from these waves ($B \sim f_c/28$, f_c in Hz, B in nT) was found to peak near 02:37 SCET at values near ~ 10000 nT. As indicated in Figure 1, at radial distances interior to the torus ($r < \sim 2.3 R_s$), the extremely low plasma density and correspondingly large magnetic fields gives rise to an under-dense plasma condition where the electron plasma frequency is much smaller than the electron cyclotron frequency $f_p \ll f_c$.

[6] As indicated in Figure 1, between 03:00–04:00 SCET, when the spacecraft was in this underdense region adjacent to the torus inner edge, a set of narrowband emissions are observed. In the figure, these appear as clusters of bands near 7 kHz, 20 kHz, and 50 kHz. The narrowband emission and their occurrence adjacent to the steep torus inner edge is reminiscent of electromagnetic ordinary (O) mode narrowband emission from the terrestrial plasmaphere [Gurnett, 1975; Jones, 1976; Kurth *et al.*, 1981] and Io plasma torus [Gurnett *et al.*, 1983a; Kurth *et al.*, 2001]. Narrowband emissions were also reported during the previous Voyager/Saturnian encounter [Gurnett *et al.*, 1981; Kurth, 1992]. However, we demonstrate herein that the narrowband emission in Figure 1, in regions where $f_c \gg f_p$, are very different from the Earth and Jupiter cases, most likely being Z-mode emission.

2. Observations

[7] Figure 2 shows high temporal and spectral resolution RPWS Wideband Receiver (WBR) spectrograms from

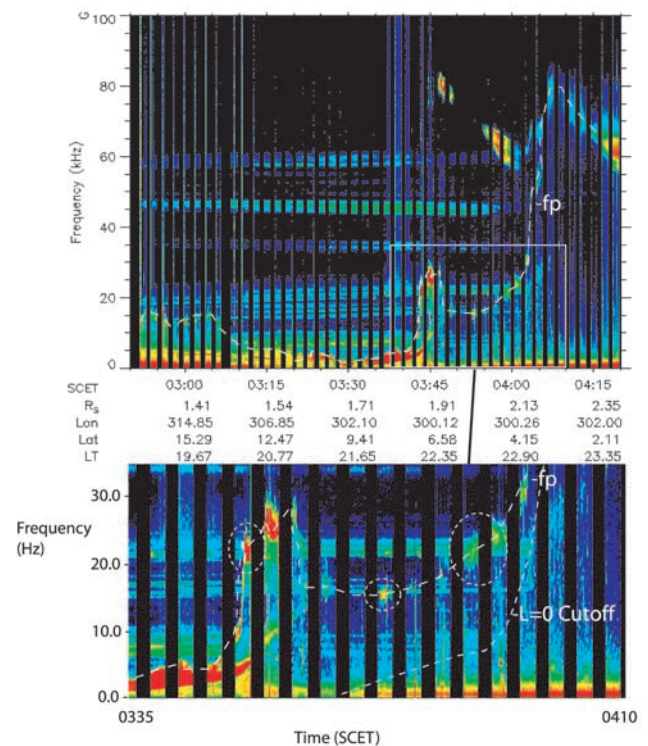


Figure 2. A Cassini RPWS wideband waveform spectrogram showing the narrow tones in high frequency resolution. An inset expanding the boxed region is also shown.

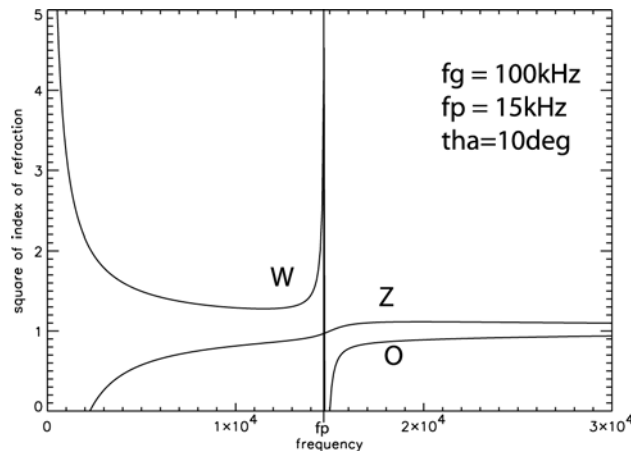


Figure 3. Cold plasma modes in low density region where narrowband emissions are observed.

02:50–04:20 SCET in a frequency range up to 100 kHz. Included is an inset focusing on emissions during 03:35–04:10 SCET. The f_p emission/electron plasma oscillation from inner edge of the torus is observed while the spacecraft is outbound from 03:30–04:07 SCET. This f_p emission quickly rises from ~ 1.5 kHz near 03:30 SCET to 85 kHz at 04:07 SCET (or electron density from 0.04/cc to near peak levels of ~ 90 /cc) in just $\sim 1/2$ a planetary radius. We also note the presence of a local high density upwelling, or “density finger” centered at 03:45 SCET, that raised the local electron plasma frequency to from ~ 5 kHz to ~ 30 kHz (or density from ~ 0.3 /cc to ~ 11 /cc).

[8] In the figure, numerous narrowband tones are detected throughout this period, observed primarily in the low density region adjacent to the torus inner edge before 04:05 SCET. Note that there are at least 16 individual tones between 5 and 60 kHz, with band widths varying from a few hundred Hz to ~ 2 kHz, depending upon the tone. The tones also drift in frequency as a function of time. Those tones below 30 kHz appear to progressively increase in frequency at a rate of about 5 kHz/hour while the intense tone near 35 kHz appears to progressively down drift in frequency at a rate of about ~ 3 kHz/hour.

[9] In some cases, the tones appear most intense at frequencies and times coincident with intense f_p emission. For example, at 04:00 SCET, the tones between 20–22 kHz appear to intensify at a location where there is intense f_p activity, suggesting that the two emissions are intimately linked. There are numerous other examples of this intense f_p wave/narrowband emission coincidence, indicated by the circles in the inset of Figure 2.

[10] At other planets, such narrowband tones have been found to be O-mode emission. However, we suggest that the tones adjacent to the torus at Saturn are Z-mode for three reasons:

[11] First, the Z-mode is a viable branch in this magneto-plasma environment. Figure 3 shows a calculation of the plasma modes using cold plasma approximations [Stix, 1962; Gurnett and Bhattacharjee, 2005]. As indicated in the figure, for plasma conditions like that in the underdense region in Figure 2, the whistler, Z, and O modes all exist, with the whistler mode becoming strongly electrostatic

(large n) near its resonance at f_p , and O-mode ceasing at its cut off at f_p . In regions where $f > f_p$, the Z-mode is viable, and as likely to be the propagation mode as the O-mode, particularly given their similar n values.

[12] Second, while the O-mode does not extend to frequencies below f_p , the Z-mode branch smoothly extends through f_p , and hence can propagate directly into high density structures. Figure 3 shows the Z-mode branch that smoothly extends from above to below f_p in underdense plasma conditions. The inset of Figure 2 shows the density “finger” at 03:45 SCET, with narrowband tones easily passing through the density structure (in some cases, without a noticeable change in signal strength) consistent with a Z-mode emission. An O-mode emission would not propagate into regions where $f < f_p$. There are numerous other examples of these Saturnian narrowband emissions propagating into high-density regions forbidden to the O-mode.

[13] Finally, as indicated in Figure 2, the narrowband tones propagate into the high density region after 03:55 SCET, in regions where $f < f_p$, and cease propagation at the $L = 0$ cutoff, consistent with the Z-mode. As indicated in the figure, the emissions are propagating into a medium with electron plasma frequency (density) increasing quickly from $f_p \sim 17$ kHz to 80 kHz. The $L = 0$ cutoff is also indicated in the figure (in low densities, $f_{L=0} \sim f_p^2/f_c$). Note that the tones are observed at frequencies, $f > f_{L=0}$, but not regions where $f < f_{L=0}$. The Z-mode low frequency limit is defined by the $L = 0$ cutoff, and the cessation of propagation at this $f = f_{L=0}$ is consistent with the Z-mode.

[14] There are both similarities and differences between the inner Saturnian Torus and the low density regions associated with terrestrial auroral activity (i.e., auroral plasma cavities). In both cases, $f_p < f_c$ and within these regions, intense f_p waves, auroral hiss (electrostatic whistler mode emission) and Z-mode emissions are all present [Gurnett *et al.*, 1983b, 2005]. In the terrestrial aurora case, narrowband Z-mode emissions are observed, but appear as trapped emissions congregating/accumulating near the $L = 0$ cut off (where the group velocity tends toward zero) at frequencies below both f_p and f_c (see Figure 6 of Gurnett *et al.* [1983b]). In the Saturnian case, the narrowband emission are not bound to frequencies near the $L = 0$ cutoff, but instead easily propagate from very high into very low densities. Thus, while plasma conditions are the same and Z-mode is present in both cases, the narrowband emissions appear to be fundamentally different.

[15] As the inset in Figure 2 suggests, there is an interesting coincidence of narrowband tones and f_p wave intensification (regions identified with circles). This association suggests that these electrostatic emissions are involved in generating the Z-mode tones, and this connection might be involved in explaining the intrinsic narrow bandwidth of the tones. Not every tone (and especially those at higher frequencies) has an associated f_p intensification source point (for example, the emission at ~ 35 kHz in Figure 2), suggesting that Cassini did not make a direct passage through these Z-mode tone source regions. In these cases, the emitted tones are sensed remotely from their active source region.

[16] In close examination of spectrograms, we also note a number of contrary cases. For example, in Figure 2, the intense f_p emission at 03:45 SCET near 25 kHz does not

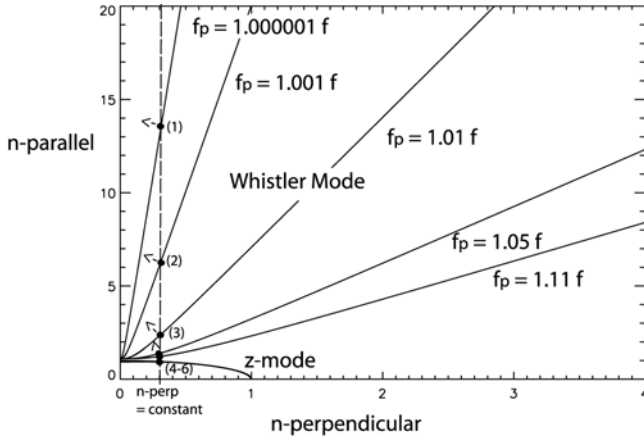


Figure 4. The index of refraction surfaces for Z-mode and whistler mode emissions in a plasma with density increasing by $\sim 22\%$. Note that the whistler mode resonance cone expands with increasing frequency.

give rise to an obvious narrowband Z-mode tone. We thus surmise that f_p intensifications alone are not sufficient conditions for the emission to occur. Also, the set of tones at low frequencies near 8 kHz appear to cease at or near f_p around 03:43 SCET (suggesting O-mode emission), but are then observed again at later times ($>03:46$ SCET) at frequencies well below f_p but with greatly diminished intensities. Obviously, activity during this period is very complicated. Thus, while we show evidence for Z-mode, we do not rule out that O-mode tones (entire tone or tones with a mix mode) may also be present.

[17] *Gurnett et al.* [1981] previously reported on narrowband emissions observed by Voyager in the Saturn's magnetosphere. These observations were made far from Saturn, at radial distances beyond the torus, mostly in regions where the wave frequency exceeded the local electron plasma and cyclotron frequencies. It was concluded that these external emissions were on the O-mode branch. *Gurnett et al.* suggested that the frequency spacing of some of the bands indicated an electron cyclotron harmonic structure consistent with locations associated with some of the major moons of the planet. *Jones* [1980] applied his linear wave mode conversion theory to explain the tones, suggesting that the emission origin was a density ledge, possibly being the reported outer torus region. These torus-external narrowband emissions reported by *Gurnett et al.* [1981] appear to differ from the emissions in Figure 2, the two being of fundamentally different modes. Cassini also observed narrow tones in the region external to the torus, but this work focuses on the unusual Z-mode tones found interior to the torus at $r < 2.2$ Rs.

[18] A fundamental question regarding the Z-mode tones in Figure 2: How does intense f_p emission apparently located at the emission source interact with and create the Z-mode? Figure 3 implicitly suggests a method for coupling f_p to the Z-mode via the whistler mode (W). Specifically, the limiting frequency of the whistler mode branch is the plasma frequency, and the limiting mode at resonance is the electrostatic plasma oscillation. In a situation where the plasma frequency (density) is steadily increasing, intense electrostatic emission near f_p will progressively move down

the W branch, to the local minima located at frequencies just below f_p and close to the Z-mode branch. This location allows a mode conversion from W to Z mode. In Figure 3, emission conversion frequency lies at about $0.9 f_p$. The intrinsic narrowband nature of the signal results from the "U"-shaped topology of the whistler branch, allowing W/Z mode conversion to maximize at the local minimum along the branch (i.e., at the bottom of the "U"). In essence, the whistler emission evolves from an electrostatic to electromagnetic nature as f_p (density) increases. Once on the Z-mode, emissions propagate easily through density structures. Note also that for wave emissions above f_p , the Z and O mode branches are in close proximity and some further coupling to O-mode may occur.

[19] This mode conversion process has some similarities to that proposed by *Jones* [1976] in the generation of narrow tones in the terrestrial magnetosphere. He suggested that electrostatic UH emissions, in changing plasma conditions, move down the Z-mode branch to locations where Z and O-mode branches are in proximity, thereby allowing mode conversion to escaping O-mode. Figure 6a of *Kaiser et al.* [1993] displays this UH-to- Z-to-O mode coupling for f_c comparable to, but larger than f_p ($f_c \gg f_p$). In the case here, $f_c \gg f_p$, moving the whistler branch closer to the Z-mode, thereby connecting electrostatic emission near f_p to the Z-mode, via the whistler mode branch (f_p -to-W-to-Z).

3. Theory

[20] To illustrate this coupling process more exactly, a parallel presentation is made to that of *Jones* [1976]. In order to arrive at an explicit solution, a number of assumptions are required. First, it is assumed that there is intense f_p emission/plasma oscillations with $k_{\parallel} > k_{\perp}$. The observations of intense activity in the circled regions of Figure 2 make this assumption reasonable. Second, we assume that the gradient in density is along the magnetic field line, such that $\nabla n \parallel B$. This condition differs from *Jones* [1976], who applied $\nabla n \perp B$. However, the statement of gradient orientation is vital to both works, since it constrains the index of refraction as the ray moves in the changing plasma environment. Finally, it is assumed that the emission source is located at a local minimum in density, and that the rays initially propagate into higher density regions.

[21] We now examine the index of refraction for waves with f near f_p in these conditions. Figure 4 shows the index of refraction surfaces derived from cold plasma theory [*Stix*, 1962; *Gurnett and Bhattacharjee*, 2005] for both the whistler and Z-modes in the case of $f = 15$ kHz and $f_c \sim 100$ kHz. The modes are shown in a situation where f_p is increasing from near 15 to 16.5 kHz. Note that for f_p increasing by $\sim 11\%$, the Z-mode topology is approximately constant (being the curve below $n_{\parallel} \sim <1$), with the topological appearance of an ellipse in k -space (or n -space). However, the whistler mode topologically appears as a magnetic-field centered cone in k -space, often referred to as the resonance cone. The resonance cone angle, Ψ , is the angle defined by the magnetic field and the surface-normal to the conical portion of the index-of-refraction surface. The wave normal angle, θ , is defined as the angle between the magnetic field vector and index of refraction vector. Consequently, for whistler mode emissions propagating on

the resonance cone, $\Psi = 90^\circ - \theta$. Note that as f_p increases, the wave normal angle increases and correspondingly resonance cone angle decreases. Thus, the cones become enlarged with increasing f_p .

[22] Consider the intense f_p emission observed in the circles of Figure 2. Such emission lies very close to the resonance at f_p of the W branch, as illustrated in Figure 3, with a very large index of refraction value. Such an electrostatic emission could be located, for example, at point (1) in Figure 4. In this example, we arbitrarily choose an initial n_{\parallel} value near 15 so that the Z-mode curves are conveniently illustrated on the plot, but the argument applies for any large n_{\parallel} value (e.g., $n_{\parallel} = 50, 100$, etc.).

[23] As stated in the assumptions, we consider that the intense electrostatic f_p emission is located in a local density minimum. The ray at point (1) (illustrated by the arrow) directs the wave into increasing densities, and correspondingly, the perpendicular index of refraction is constrained by Snell's law: the index component tangential to the gradient (and to B) is constant, $n_{\perp} = \text{constant}$. Consequently, as the ray moves into increasing densities, it will migrate to points (2), (3), (4), and (5) as the plasma frequency increases by 0.1%, 1%, 5%, and 11%, respectively. With just a small change in density ($\sim 22\%$), the mode moves from primarily electrostatic ($n \gg 1$) to electromagnetic ($n \sim 1$) in nature. At point (5), the whistler-mode index is almost identical to that of the Z-mode and energy can easily couple to the Z-mode. Once on the Z-mode branch, the emissions can escape any density structure since the Z-mode is near unity both above and below f_p (see Figure 3).

[24] One can demonstrate the process in Figure 4 analytically. Specifically, the electrostatic whistler emissions are propagating with wave normals on the resonance cone. The resonance cone angle, Ψ , is defined as [Gurnett et al., 1986; Farrell et al., 1988]

$$\tan^2 \Psi = -S/P = -\left(1 - (f_p/f)^2\right)^{-1} \quad (1)$$

with

$$\sin \Psi = f/f_p = \cos \theta \quad (2)$$

Equation (2) uses the fact that the resonance cone angle for electrostatic whistler-mode emissions is the complementary angle to the wave normal angle, θ . Snell's law confines the perpendicular index to a constant value which can be written with equation (2) as

$$n \sin \theta = n \left(1 - f^2/f_p^2\right)^{1/2} = \text{constant} \quad (3)$$

The origin of activity (conditions designated by “o” symbol) is the local density minimum where the electrostatic waves are strong, $f \sim f_{po}$ and $n = n_o$, making

$$n \sin \theta = n \left(1 - f^2/f_p^2\right)^{1/2} = n_o \epsilon \quad (4)$$

where n_o is the large index of refraction for the local electrostatic wave (10–300) and ϵ is the very small value of $(1 - f^2/f_{po}^2)^{1/2}$. To couple to the Z-mode, $n_o \epsilon = n_{\perp} < 1$. From

Snell's law, equation (3), we find that as the ray propagates into adjacent higher density regions, the index of refraction becomes

$$n = n_o \epsilon / \left(1 - f^2/f_p^2\right)^{1/2} \sim n_o \epsilon / \left(1 - f_{po}^2/f_p^2\right)^{1/2} \quad (5)$$

with n progressively decreasing as f_p increases, consistent with decreasing n -values along the $n_{\perp} = \text{constant}$ line in Figure 4. The emission goes from extreme electrostatic (large n) to electromagnetic ($n \sim 1$) when propagating into a medium of increasing density. This formalism breaks down as n approaches 1, since the whistler mode wave normal angle is no longer complementary to the resonance cone angle.

[25] As an example application, consider an electrostatic plasma frequency emission generated via enhanced thermal processes such that $k \sim \omega_p/v_{th}$, where v_{th} is the electron thermal velocity. For a 1 eV electron temperature, the emission has $n_o \sim c/v_{th} \sim 500$. We also assume the emissions are quasi-parallel, but with some oblique energy extending to at least $\theta \sim 0.06^\circ$. At this angle, $\sin \theta = \epsilon = 10^{-3}$ and the emission will lie on the electrostatic portion of the whistler mode branch (very near resonance) at frequency $f = (1 - \epsilon^2/2) f_{po}$. As this emission propagates into denser plasma, the associated index of refraction defined by equation (5) becomes 35.3, 11.2, 3.6, and 1.2 for a progressively increasing plasma frequency of $1.0001 f_{po}$, $1.001 f_{po}$, $1.01 f_{po}$, and $1.1 f_{po}$, respectively.

4. Conclusions

[26] Narrowband quasi-continuous tones have been observed in the Saturnian inner magnetosphere. Similar tones have been observed in the magnetospheres of the gas giants and at Earth, identified as O-mode emissions. However, we demonstrate here that the particular emission interior to the plasma torus, are propagating in the Z-mode. This conclusion is based on the viability of the mode at the emission frequencies, the emission propagation into well-defined density structures and the emission cut off at $L = 0$.

[27] We suggest that the emission is generated from mode conversion of intense electrostatic f_p emission into Z-mode via whistler-mode propagation into increasing densities. While explaining the narrow bandwidth of the emission and emission occurrence with intense f_p burst, this mechanism is not unique and other possible explanations that fit the observations may also be viable. However, the whistler mode branch extends from large n values near f_p to small values just below f_p and provides a simple pathway for the electrostatic energy at large n to migrate near the Z-mode branch with $n \sim 1$.

[28] The relevance of the narrowband Z-mode emission may extend beyond simply being a curiosity: the tones observed remotely from their source may be indicative of active region temporal evolution. One (nonunique) interpretation is that the tone temporal variation is associated with changes in local plasma density at their source. In this interpretation, the tones allow us to sense the density movement along the inner torus edge about 45 minutes prior to actual spacecraft interception with the torus wall. Consider the narrowband tones generated at 04:00 SCET near 23 kHz (see Figure 2). Emission from this source

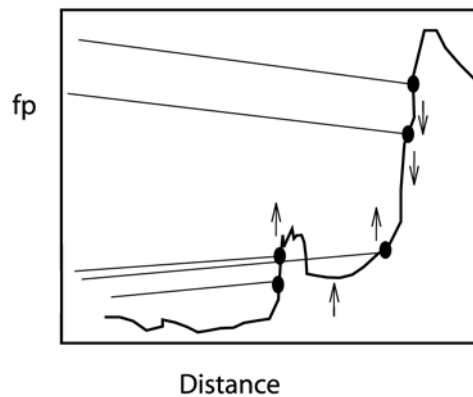


Figure 5. Illustrated is the evolution of the torus inner edge or “wall” to account for the observed updrifting and downdrifting tones. The foot region of the wall is steadily increasing in density (plasma frequency), creating the remotely observed updrifting tones, while the steep portion of the wall is decreasing in density, creating the corresponding downdrifting tones.

appears to have been observed by the spacecraft prior to 03:15 SCET, with the tone continuously present for the ~ 45 minute interval appearing as a gradual updrifting emission with a drift rate at 4–5 kHz/hour. Such an observation suggests that the inner-torus active source region had a plasma frequency (density) that steadily increased over the 45 minute period. Nearly all the tones observed below 25 kHz show a similar updrift, possibly suggesting that the radially inner most pedestal or “foot” region of the torus wall (03:40–04:00 SCET) is undergoing an “upwelling” or bulk increase in plasma density. The observed updrifts are consistent with an increase in plasma density on the order of $\Delta n/n \sim 25\%$ over the 45 minute interval. Figure 5 illustrates the situation. In contrast, the tones between 30–50 kHz are downdrifting at a rate of -3 kHz/hour, suggesting that their sources located in along the steepest portion of the torus wall are losing plasma over time. The observed downdrift between 30–50 kHz is consistent with a $\Delta n/n \sim -10\%$ loss in plasma density over the time period. Hence, the tones allow investigators to monitor the temporal evolution of the torus via

the remote-sensed Z-mode waves detected nearly an hour before the actual Cassini/torus encounter. The results indicate that the inner torus wall undergoes slow, steady plasma density changes over the period of observation.

[29] **Acknowledgment.** Arthur Richmond thanks Christopher T. Russell for his assistance in evaluating this paper.

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